VARIANT FLEXIBLE HAIRPIN STATOR (E-MOTOR) PRODUCTION THROUGH PARAMETRIC MODELING AND ADDITIVE TOOLING

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ABSTRACT

In Additive Manufacturing (AM), the method of Parametric Modeling (PM) is often used for the design development and creation of products. However, this approach is not yet widely used for the development of tools for production machines and processes. In the production of hairpin stators (an innovative technology for the copper winding of the static component of an electric motor for electric vehicles) in the field of e-mobility, the demands for variant flexible production lines are increasing in order to react to the short development cycles of electric motors in a more cost-efficient way. Therefore, the goal is to achieve this variant flexibility in the production of hairpin stators through Parametric Modeling and Additive Tooling (AT) of production tools depending on product characteristics. For this purpose, parametric models of developed tools are generated by implementing design algorithms in parametric design software. By varying the input parameters of the product, e.g. the desired properties of the stator, the required variant flexibility is validated. The work is exemplified for one production step of hairpin stator production on a clamping tool for welding hairpins (copper conductors). Results confirm that a combination of Parametric Modelling and Additive Tooling has the potential of achieving variant flexible production lines and decreasing the amount of effort for development cycles.

KEYWORDS

Additive Tooling; Design for Additive Manufacturing; Parametric Modeling; Design Scripting, Hairpin Stator; Hairpin Stator Production; Variant Flexibility; Electric Machines; E-Mobility

INTRODUCTION

In the field of e-mobility, the so-called hairpin technology has become established in the automotive sector in recent years for the winding of electric traction machines. The winding consists of the current-carrying copper conductors that generate the rotating magnetic field of an e-machine. OEMs such as VW, Porsche, Audi, Hyundai, BMW, Ford, Toyota or suppliers such as Borg Warner, Schaeffler, Mahle, Marelli and ZF now use hairpin stators in their e-machines. Hairpin technology uses electrical copper conductors with a rectangular wire cross-section instead of round copper wire wound into the slots of the stator - the stationary component of an e-machine. A large number of these copper conductors are bent into the so-called hairpin shape outside the stator and then mounted in the stator laminations and welded to form a continuous coil (Figure 1, left). The entire production process chain is shown in Figure 2 and can be divided into the main areas of hairpin forming, assembly, twisting, welding and impregnation/ end-of-line (EoL). Hairpin technology has several advantages over conventional windings on the product and production side. The copper fill factor - the ratio of copper to insulating materials and empty space - for conductors with a rectangular cross-section (73%) is significantly higher than for round wire (45%), shown in Figure 1, right [1, 2]. Due to the larger conductor cross-sectional area, the electrical resistance in the conductor is also lower and more current can flow through the conductor at the same voltage level. At constant temperature, the conductor resistance is only dependent on the quotient of conductor length and conductor cross-sectional area. An increased cross-sectional area leads to lower resistance, allowing an increase in power.

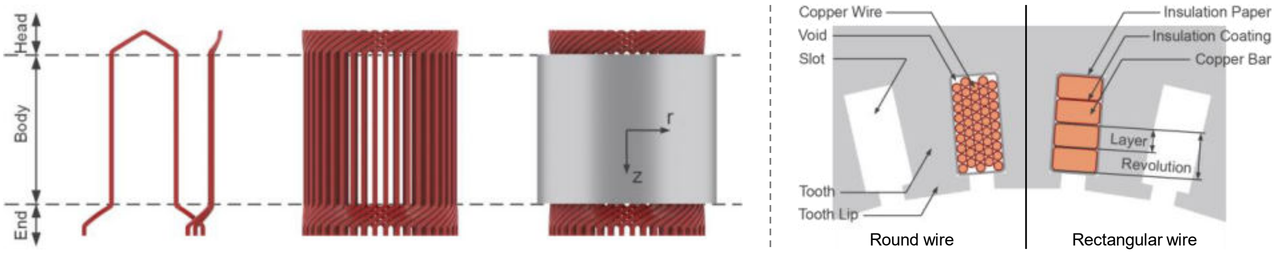


Figure 1: Single Hairpin, Hairpin Winding, Hairpin Winding in Stator (left); Stator Slot Cross-Sections (right)

Due to the advantages mentioned above, the power density and efficiency of hairpin stators are higher than those of conventionally wound stators [3]. On the production side, the external bending and targeted insertion of the hairpin copper conductors results in a deterministic production process with a high degree of automation compared to the more stochastic winding of round wire. However, due to the larger conductor cross-sectional area, electromagnetic effects also occur in the frequency range of automotive applications, leading to eddy currents and current displacement in the conductors and thus to losses. [4, 5]

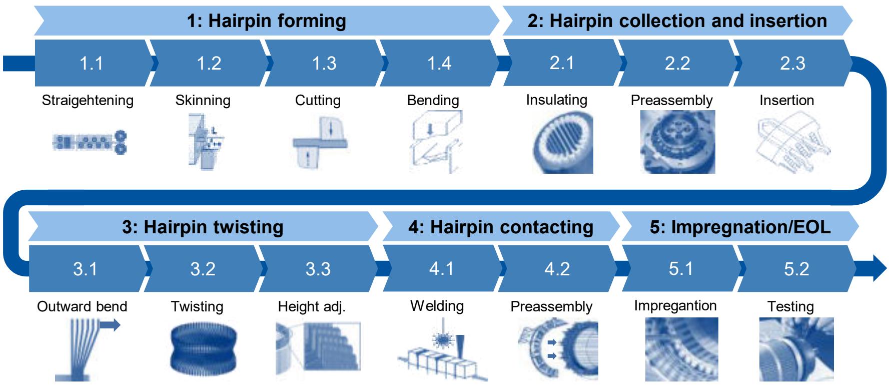


Figure 2: Hairpin Production Process [6]

The machine investment of a hairpin stator production line for OEMs and supplier companies is high and only pays off when approx-imately 200,000 hairpin stators are produced [1]. The equipment in hairpin stator production lines, as well as their tools and devices, are for the most part designed for only one special type of stator and copper wire. The ramp-up times of hairpin stator production lines are sometimes quite long. By contrast, the development cycles for new generations of electric machines in the automotive sector are shorter than for internal combustion engines. As a result, the targeted number of hairpin stators produced is not achieved and equipment must be replaced when a new generation of stators is developed. This calls for variant-flexible production equipment in hairpin stator production in order to increase the number of units in the production lines. Variant flexibility enables the production of different variants of hairpin stators on the same production line without the need to renew entire equipment and therefore reduces production downtime. In recent years, some research and further development of hairpin stator production has been carried out, but the lack of flexibility remains a major problem in terms of cost. [7, 8, 9, 10, 11, 12]

In the field of AM, tooling often falls under the term rapid tooling, which does not directly imply AM. The reality of rapid, short-term production, on the other hand, does. Figure 3, left, based on *Gebhardt* describes the contexts and was extended by the term of the AT, because design und material selection are supposed to be adjusted depending on the different purposes, even though the using technologies are the same. [13, 14] AT therefore offers a way to address the variant flexibility described for the tools of hairpin stator production lines. Therefore, due to the higher design freedom in the field of AM, new approaches and tools such as PM or algorithm aided design can be used in the design development process. Parametric CAD modeling is a different concept in comparison to conventional CAD with drawing 2D surfaces and extrusion afterwards. Rather than directly creating solid elements in the model space, PM is to write a design script in a different way.

In the script, different entities can be associated with so called constraints. Due to the constraints, the changes in parameters can interact with associated entities that can immediately reflect in the CAD model. For this reason, there is the powerful ability to rapidly generate variant models.

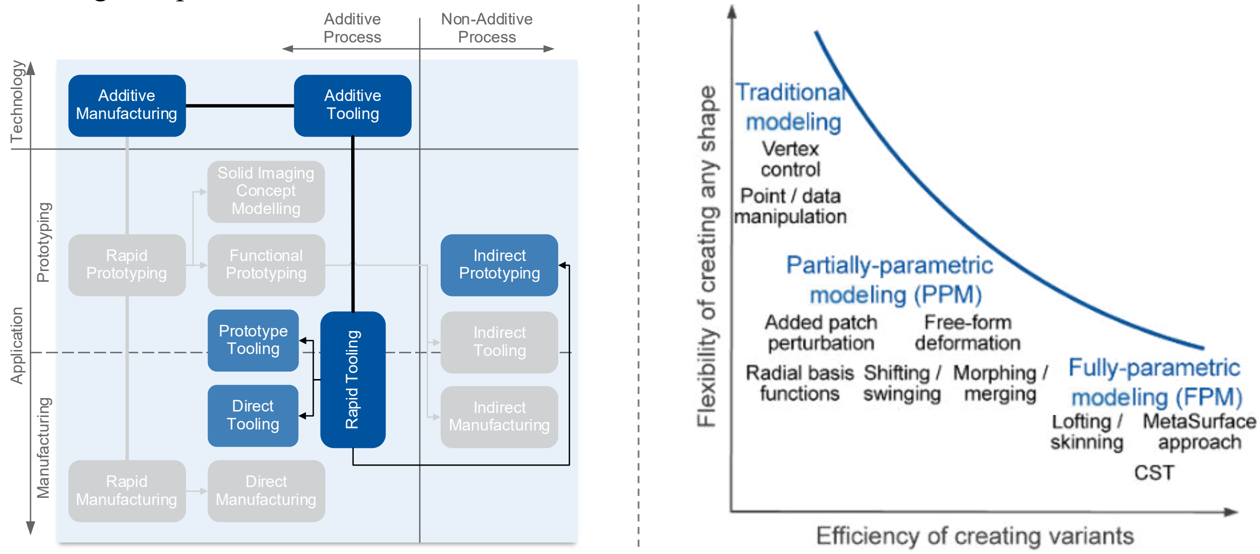


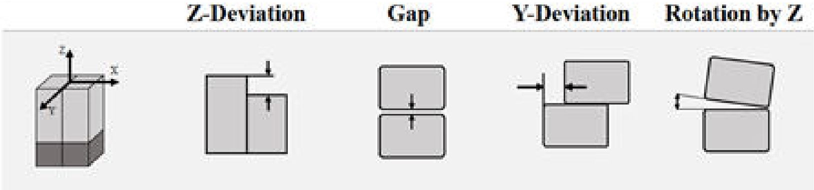
Figure 3: Classification Additive Tooling (left) [13, 14]; Types of Parametric Modeling (right) [15]

The specific interaction of PM and AT therefore holds great potential for integrating variant flexibility into production processes of physical products.

1. DEVELOPMENT OF VARIANT FLEXIBLE TOOL CONCEPTS FOR AT

The process step 4.1 of contacting (Figure 2) represents one of the most critical process steps in inflexible manufacturing. For this reason, the development of a variant-flexible tool concept and the parametric modeling is demonstrated on the corresponding tool of this process step. In the contacting process, the free hairpin ends on the opposite side from the bent winding head side are each welded together in pairs to obtain continuous coils per phase in the winding. The number of welding points is calculated by multiplying the number of stator slots by the conductor pairs per slot and is often several 100 welding points. If only one welding deviates from the nominal welding, the stator becomes unusable. In this case, clamping tools and devices are necessary to create the appropriate joints between adjacent hairpin ends for the welding process.

The development of the tool concept is classically carried out based on the product development process (PDP) according to *VDI 2221* [16]. In addition to functional requirements, the focus here is primarily on requirements relating to variant flexibility. In the present development, variant flexibility results primarily from two different stator variants, for which a production line is to be developed, built and researched in the accompanying research project. Both variants are to be produced on the same line. An excerpt of the parameters and properties of the two stator variants is shown in the following Figure 5. Productivity and cycle time are also requirements that should not be neglected. Based on the requirements, the functional structure of the clamping tool for the welding process can be set up. The main function is "clamping the hairpin ends" and can be abstracted into many other secondary functions. The decisive factor here is that the hairpin ends must be clamped in the radial and tangential direction of the stator. The hairpin ends are arranged in a tolerance zone before clamping



	Z-Deviation	Gap	Y-Deviation	Rotation by Z
Actual	max. 2,2 mm	max. 0,25 mm	max. 0,95 mm	max. 0,25 mm
Target	max. 1,1 mm	max. 0,1 mm	max. 0,5 mm	max. 0,1 mm

Figure 4: Tolerance Zone of previous Process Step [17]

(Figure 4). The tool concept must therefore be able to take these tolerances into account.

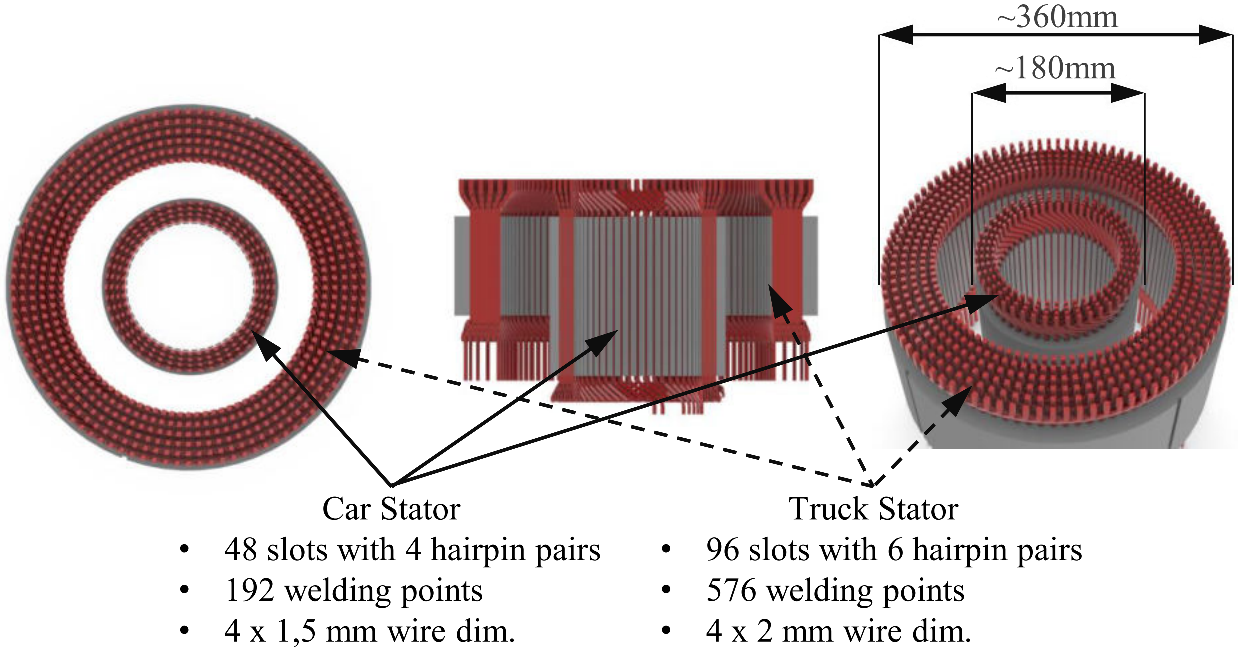


Figure 5: Hairpin Stator Variants and Properties (for Comparison of Dimensions the Car Stator is shown within the Truck Stator), left: top view, middle: cross section

Furthermore, the welding process generates spatter and a high temperature load near the clamping surfaces of the tool. With regard to variant flexibility, the following main functions should be mentioned: Adapt variant dimensions of hairpins, arrangements of hairpins, dimensions of the stator. These functions are further divided into more abstract subfunctions. In the selection of principle solutions for the corresponding sub-functions, the potential of AM in particular is considered and focused on, such as function integration and design for AM. The selected AM manufacturing process for the tool to be developed is the Laser Powder Bed Fusion (LPBF) process. The individual principle solutions are bundled into a morphological box. After the selection of target-oriented principle solutions in the morphological box, an initial overall concept can then be derived. Here, it is already necessary to consider a trade-off between the conflicting target requirements of variant flexibility and productivity. To achieve a certain degree of variant flexibility while keeping productivity in the welding process high, all hairpin ends in one row (radial) of the stator are clamped simultaneously. In the conceptual design of the clamping tool, a design consisting of two components proves to be target-oriented. The first component, the lower clamping tool, is used for clamping in the radial direction (Figure 6, red). The second component, the upper clamping tool, is used for tangential clamping (Figure 6, blue).

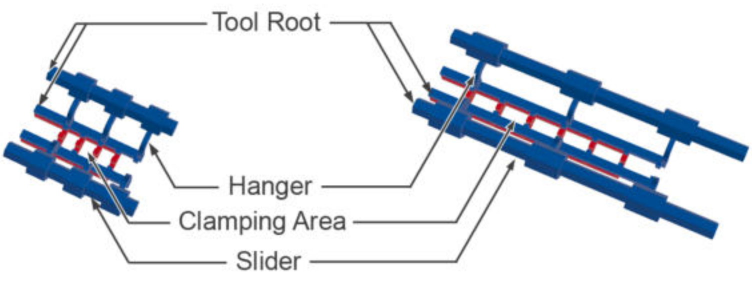
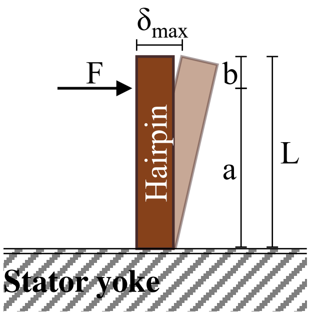


Figure 6: Clamping Tool Concept for Car (left) and Truck (right) Hairpin Stator, Upper Part (blue), Lower Part (red)

During the development of the final design from the concept, calculations of forces acting on the tool are also carried out. To avoid underestimation of resulting forces, it is assumed that the clamping tools must be able to plastically deform the free hairpin ends during clamping. The geometric limits of deformation (δ_{max}) depend on the tolerance zone (Figure 4). In the real application, however, the clamping tool only has to overcome spring back forces of the copper conductors. The problem can be abstracted to a beam clamped on one side (Figure 7). Thus, the forces required to bend a hairpin end for the upper tool are calculated to be 2.2 N for radial clamping and 34.5 N for tangential clamping. For the lower tool it is 2,5 N for radial clamping.



$$F = \frac{\delta_{max} * 6EI}{a^2(3L - a)} \tag{1}$$

F: Applied force [N]
E: Young's modulus copper [N/mm²]
δ_{max} : Displacement [mm]
a: Distance between fixed end and force [mm]
L: Total lenght of hairpin end [mm]
I: Area (cross-section) moment of inertia [mm^4]

Figure 7: Calculation of Clamp Forces for Hairpin Displacement

By means of FEM simulations with the calculated forces of the tool design, the existing stress behavior is determined and a material selection is carried out. The design and the material are iteratively adjusted until the simulated stress behavior is below a certain level and a sufficient safety factor for the selected material is achieved.
Finally, the tool design is then optimized for the LPBF manufacturing process by making adjustments appropriate to the part orientation to allow support-free manufacturing at certain user defined areas of the tool structure. The adjustments include rounding at unfavorable edges and additions of transitions with sufficient build-up angles at critical overhangs.

2. DESIGN SCRIPTING FOR PARAMETRIC MODEL IMPLEMENTATION

In the development of products for additive manufacturing, the process chain is digital throughout. Due to this digital character and the greater design freedom in the configuration of products or tools, new methods can be used for design creation. Here, generative design, shape optimization, topology optimization, PM, algorithm aided design and design scripting should be mentioned. [18, 19]
In order to make the developed tool design for the welding process in hairpin stator production even more variant-flexible, a parametric model of the clamping tool is implemented in the Rhinoceros3D (Rhino3D) software as a design algorithm by means of design scripting. Rhino3D is a commercial software solution for creating, editing and processing nurbs curves, surfaces and solids as well as point clouds and polygon meshes. It allows the modeling of almost unlimited complex 3D freeforms and the plug-in Grasshopper provides a graphical interface to implement algorithms for 3D design creation. Rhino3D was chosen because of the comparatively low licensing costs, a large community and additional developer tools for research and development. [20] The structure of the design algorithm is chosen here so that the tool design is generated depending on the product properties of the hairpin stator. The parameters and properties of the product to be manufactured thus serve as input for the design algorithm of the tool. (Figure 8)
New product variants can be entered using a slider or by directly entering the respective parameters in text fields. By defining minimum and maximum values of the sliders and input fields, specific limits and number ranges can be set for the respective parameters. In addition to the product parameters, the geometric parameters for generating the developed tool are implemented. These model parameters determine the dimensional dependencies of the tool structures and should not be adjusted after a design has been finally developed in the PDP. Under certain conditions, however, it is necessary to adjust these parameters as well. Therefore, the model parameters are also implemented via sliders or direct input of the numerical values, respectively coupled with

parameters for fine tuning. Furthermore, there are process parameters from production, which are implemented in the algorithm. The process parameters take into account the tolerance zone of the hairpin ends, which is transferred from the previous process step from hairpin stator production (compare Figure 2 and Figure 4). Since the tool design was developed for additive manufacturing (LPBF), design and manufacturing restrictions are also implemented through manufacturing parameters. These include minimum wall thicknesses, minimum clearances, minimum and maximum diameters for channels, or even minimum build angles for support-free manufacturing, provided that the component orientation for the manufacturing process is already fixed. [21]
The input parameter section in the algorithm is followed by the data processing section. Here, the information from the input parameters is interpreted and further processed. Points for geometry generation of the three-dimensional tool design are calculated and restrictions resulting from the design or also from manufacturing are translated into logic operators and implemented. For the calculation of geometry relevant points often simple mathematical operators are sufficient, which have to be implemented in the context of the tool design. Subsequently, the calculated points can be used with the decisions from the logic operators to finally generate the structure and the three-dimensional design in the object modeling section. It should be noted that the individual calculated points for generating the tool components should be aligned relative to the global origin coordinate system (0,0,0) and no exact coordinates should be specified. The points of the subcomponents of the tool components must then in turn be defined relative to the coordinate system of the next higher component (hierarchically). The relative and parameterized points can then be connected to lines, the lines to structures, the structures to surfaces and connected surfaces to solids. Here functions and operators are used, which are partly known from conventional CAD modeling software. Finally, in the assembly section of the design algorithm, all generated solids of the subcomponents are unified to form the tool components, and the finished solid model can be exported as a CAD file format. Finally, for the data preparation of the manufacturing process, the generated three-dimensional design is exported as an .STL file and can be provided to the pre-processing and slicing software. The schematic structure of the design algorithm is shown in Figure 8.

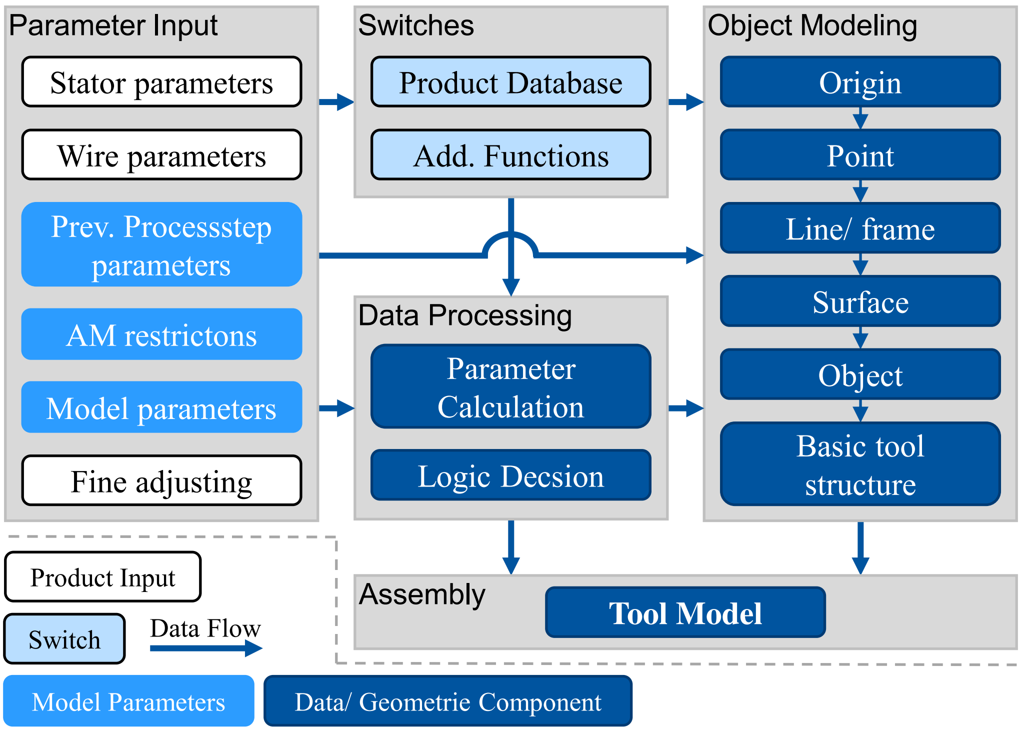


Figure 8: Schematic Structure of Design Algorithm

3. RESULTS

The final tool design in the welding process for clamping free hairpin ends is shown in the following Figure 9 for the two presented product variants of a hairpin stator. In the tool design developed, the clamping tool clamps all adjacent hairpin ends of a radial row simultaneously.

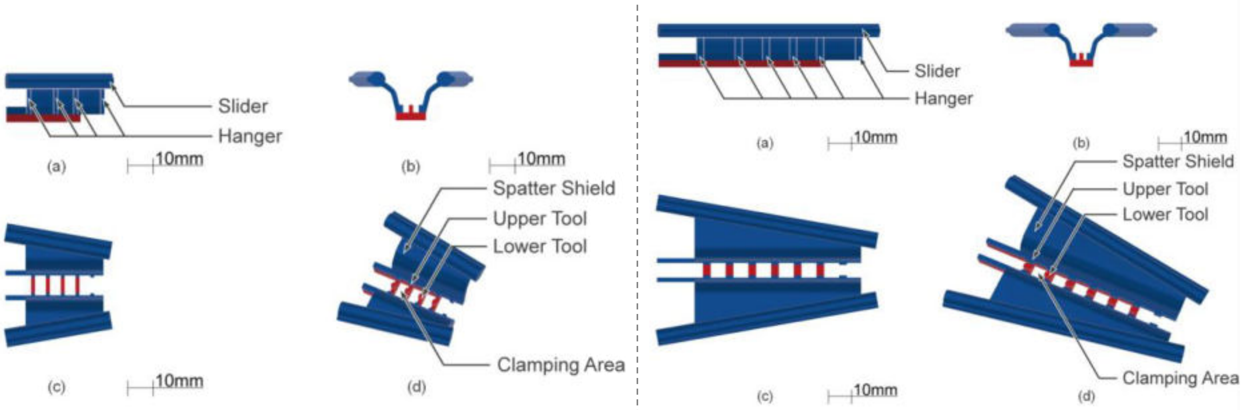


Figure 9: Final Clamping Tool Design, Car (left), Truck (right)

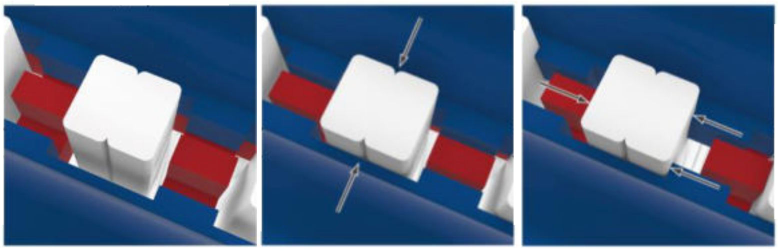


Figure 10: Movement of Tool Components for Hairpin Clamping

For this purpose, the tool unit is aligned centrally over a row of hairpins using appropriate actuators. Afterwards, the clamping tool is lowered axially (along the stator axis) between the hairpin ends so that two adjacent hairpin ends are always brought together. In the next step, the upper clamping tool is moved with the corresponding actuator to tangentially clamp the hairpin ends. After the lower clamping tool is also moved in the radial direction in the subsequent step, the clamping process is completed and the weld joints are present. Now a contacting of adjacent hairpin ends can be carried out by means of laser welding. The individual clamping tools are then released again and the tool unit is lifted in the axial direction. This completes the clamping, welding and release process and the process step can start again until all free hairpin ends have been welded in rows (radial rows). For this purpose, a rotation platform, on which the stator with the mounted hairpins is located, continues to rotate by the respective slot pitch. The concept of the rotation platform was developed by a project partner at this point.

In addition to the two solutions shown, countless other variants of the clamping tool can be generated by modifying the product parameters in the input section of the algorithm, following the same implemented design (Figure 11). The tool variants always have the same interface to the actuator system of the production plant, in order to make a tool exchange easy. The calculation time for generating a new tool design when adjusting input parameters is a few seconds (<10 sec.). The respective sections in the design algorithm are modular. New features and properties of the tool design can be added to the object modeling section of the algorithm by implementing new functions using existing data of the input and/or data processing section. Furthermore, it is possible to store complete input databases of stator variants in the algorithm. Thus, it is possible to switch between different stored products by selecting the corresponding data set and the respective tool design for the corresponding product is generated.

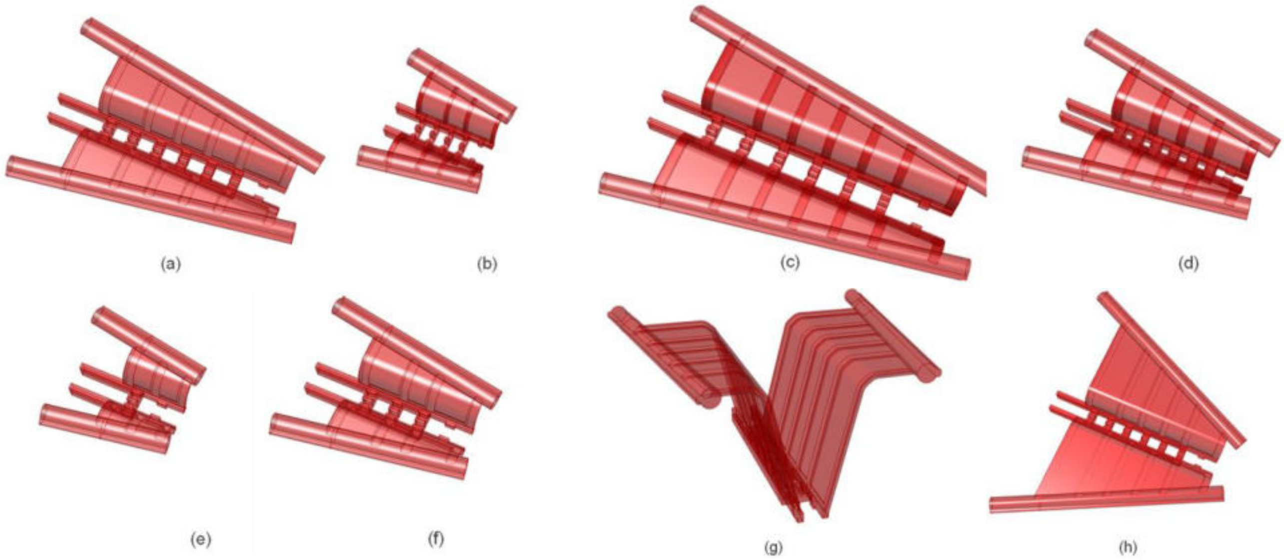


Figure 11: Variants (a) – (h) of automatically generated Tool Designs

Design for AM also makes it possible to integrate an additional function into the clamping tool. A channel for a local shielding gas flow during the welding process can be integrated into the upper clamping tool and manufactured directly using AT. Currently, industrial hairpin stator manufacturing does not use a shielding gas atmosphere during the welding process. However, further research has shown that welding under shielding gas leads to better results of the welded joint. [22, 23] The flow channel can be activated or deactivated in the design algorithm by means of an on/ off button via a boolean operator.

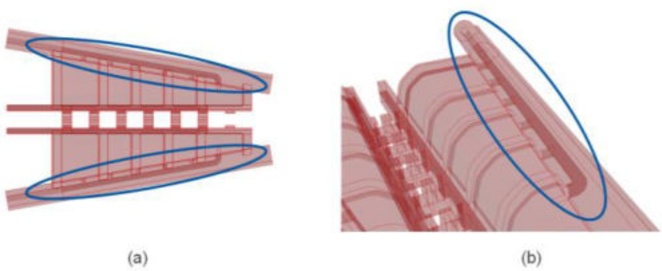


Figure 12: Integration of Shielding Gas Channel

4. DISCUSSION

The large amount of product parameters to be considered makes tool development very complex already in the concept phase. When setting up the function structure in the PDP based on the requirements and assigning the principle solutions to the individual sub-functions, it becomes clear that it is not possible to implement variant flexibility with regard to all product parameters in one concept and at the same time keep productivity high. If the clamping process for welding was restricted to a single hairpin pair, the number of variant-flexible parameters to be taken into account would be drastically reduced. With appropriate actuation of the clamping tool, ultimately only the wire geometry of the copper wire would have to be considered as a variant-flexible input of the product. However, with a number of several 100 welds, the productivity in terms of cycle time of the entire process step would be very low. Therefore, the concept developed, in which all hairpin pairs of a radial row (for the car stator 4 pairs, for the truck stator 6 pairs) are clamped simultaneously, is a good trade off in terms of variant flexibility and productivity.
However, a complete integration of variant flexibility into production processes is only possible with the present product by linking AT and PM. The developed design algorithm makes it possible for a user to enter new product parameters without profound knowledge about the structure and the individual functions of the algorithm. Tool designs adapted to the new product properties can thus be generated automatically within seconds. The following additive manufacturing of the tool thus allows new tools to be produced within a very short time. In the ramp-up phase of the production of

newly developed e-motors, the entire process of re-designing tools and fixtures is thus eliminated. The consistent interface to the existing plant also avoids the need to modify or purchase entire new production lines. Due to its modular design, the algorithm can be expanded to include new functions. However, the automatically generated designs from the design algorithm only make sense for the developed tool concept in certain parameter ranges. For example, if one specifies an unrealistic value for the number of hairpin pairs to be clamped simultaneously, the generated tool design becomes very long. Excessive bending moments due to clamping forces acting far from the interface to the actuator would probably lead to failure of the tool in use. However, with the developed tool concept, all current hairpin stator generations in the automotive sector can be addressed.

For additional adjustments to the automatically generated design for the AM process, some functions of grasshopper are not quite suitable to use for parametric modeling, such as the fillet function. The fillet function in grasshopper works according to its input regarding the line order number of a body. The order number of lines in a body is randomly assigned by the original algorithm. If additional structures or lines are added to the body, the line order of the object will change. It means that any model changes will affect the result of the fillet, and the list of line order numbers will no longer result as expected. Besides, the input diameter of the fillet function is hard to define as an accurate value or clarify the relationship with other parameters, so it frequently causes an error. For those reasons, adding fillets to the model should better be manually implemented in external, conventional CAD software after the parametric model is generated.

5. CONCLUSION

The production of hairpin stators consists of many individual process steps. Each process step involves production equipment with complex tools and devices that are designed for defined product properties and product parameters. If a product parameter changes, tools and devices often become unusable. Additive manufacturing offers the possibility of using AT to develop innovative tool and fixture concepts that can be used to produce different variants of a product. Combining the potential of AT in terms of greater design freedom with the implementation of design algorithms to PM, the variant flexibility of production process steps or the entire production line of hairpin stators can be increased. This was demonstrated using the example of the contacting process step on a clamping tool, however the methods researched and described here are not limited to the production of electric motor components. The methodology for tool development using AM and implementation of design scripts for the integration of variant flexibility can also be transferred to other production lines and products and offers potential for further research.

The research work described and the results were developed within the framework of the HaPiPro² project, which is publicly funded by the state of North Rhine-Westphalia, Germany, and is under the sponsorship of Forschungszentrum Jülich.

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